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MICROSCOPIC CHARCOAL AS A FOSSIL INDICATOR OF FIRE*

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Charcoal preserved in lake sediments, peat, and soils provides a record of past fire occurrence. An understanding of fire history is important in evaluating interactions between vegetation, climate and human disturbances through at least the last several millennia. In this paper we review information concerning the production, dispersal, sedimentation and preservation of charcoal. We present examples of studies that have used charcoal analysis in palaeoecological reconstructions, with special emphasis on analytical techniques and problems of interpretation.

Unlike pollen, which is produced continuously in fairly constant amounts, charcoal is produced in large quantities but at irregular intervals. These are a function of fire regimes that are often unique to specific vegetation types and/or climatic regions. Charcoal particles vary in size from sub-microscopic to macroscopic, with small particles presumably being transported further by wind and water than large particles. Charcoal preserves well, but it may be subject to breakage, especially when transported by water. We present theoretical models of dispersal and discuss potential problems associated with post-depositional mixing.

A variety of charcoal analysis techniques have been employed during the past four decades. Most involve microscopic identification and quantification of numbers or size of individual fragments occurring in samples prepared for pollen analysis. The most commonly used method — estimating charcoal area by categorizing particles in several size classes — is both tedious and time consuming, and recently introduced techniques attempt to estimate past fire occurrence based upon point count estimation, elemental carbon analysis, magnetic measurement of sediments, electron microscope, and spectrographic analyses. A lack of standardization both within and among analysis techniques has hampered interpretation of charcoal profiles. Taphonomic processes affecting charcoal are less well understood than for pollen, and as a result interpretations of historic interactions between vegetation and fire based upon pollen and charcoal analyses are difficult. We review several studies through which advances have been made and suggest questions for future study.

INTRODUCTION

A number of recent publications have emphasized the role of fire in effecting ecosystem change in various parts of the world (e.g. Slaughter *et al.*, 1971; Wright and Heinselman, 1973; Kozlowski and Ahlgren, 1974; Mooney and Conrad, 1977; Gill *et al.*, 1981; Wein and MacLean, 1983). Natural fires have affected vegetation throughout geological time (Harris, 1958; Komarek, 1973; Kemp, 1981), and Stewart (1956, p. 115) referred to fire as the 'first great force employed by man'. The intentional manipulation of biomass by the use of fire in prehistoric times has been suggested by some commentators (Mellars, 1976; Jacobi *et al.*, 1976; Simmons *et al.*, 1981) and documentary and ethnographic evidence attest to the rôle of fire in landscape development and natural resource management (Turnbull, 1972; Wright, 1974, 1981; R.F. Wright, 1976; Gill *et al.*, 1981).

Fire history can be reconstructed from such macroscale evidence as fire scar data from tree-ring studies (Heinselman, 1973; Zackrisson, 1977) or burnt peat or wood layers in peat (Durno and McVean, 1959; Tallis 1975). Most palaeorecords are derived from airborne or sedimentary microscopic charcoal in sites of airborne or sedimentary deposition such as peat bogs, lakes and soils. Microscopic charcoal is abundant in lakes (Waddington, 1969; Swain, 1973, 1978, 1980; Cwynar, 1978), mires (Iversen, 1941; Tallis, 1975; Simmons and Innis, 1981) and soils (Whittington, 1983). In recent years, studies of microscopic charcoal have been directed towards investigations of forest stability (Green, 1981, 1982; Walker, 1982), and studies of the effects of human disturbances on the environment (Vuorela, 1976; Edwards, 1978; Huttunen, 1980; Singh *et al.*, 1981; Tolonen, 1985).

This paper examines the utility of microscopic charcoal analysis in palaeoecological research. The emphasis is upon methodology and techniques rather than upon the ecological impacts of fire. The specific objectives of this paper are:

(1) To summarise the available information on the nature, dispersal and deposition of charcoal.

(2) To review the methods that have been used to determine the charcoal content of deposits.

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(3) To evaluate the utility of charcoal analysis techniques for investigating specific palaeoecological questions.

(4) To compare methods utilizing microscopic charcoal analysis with those which chemically or physically evaluate the abundance of charcoal in deposits.

Figure 1 depicts graphically the relationship between fires and their associated charcoal production, deposition and assessment (cf. Maguire, 1983a). The arrangement of the paper follows a similar progression.

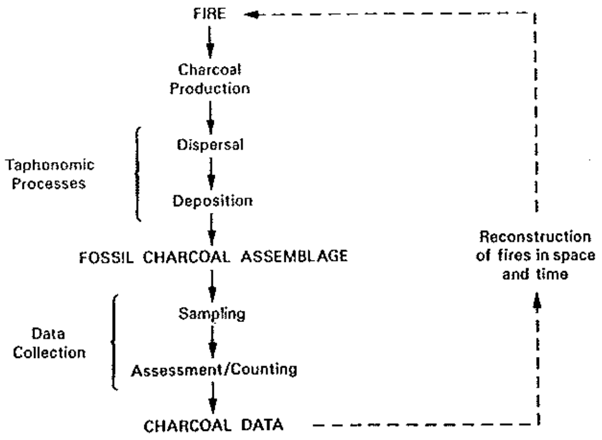

FIG. 1. Relationship between fire and charcoal and approaches for reconstruction.

CHARCOAL PRODUCTION

Charcoal is an amorphous inorganic carbon compound which results from the incomplete combustion of plant tissues. This combustion is supported by the generation of the combustible gases carbon monoxide and methane and low levels of oxygen (Cope and Chaloner, 1980, 1981; Clark and Russell, 1981). Charcoal preserves well and therefore can be used as a record of past fires (Komarek, 1973).

Natural ignition sources include spontaneous combustion, volcanic activity, meteorite fall, sparks due to rock fall, and, most importantly, lightning strike (Cope and Chaloner, 1980). The frequency of lightning discharges over the surface of the Earth is estimated at 100 per second (Komarek, 1964).

A number of factors may be expected to influence the amount and type of charcoal produced by a fire. The type of material being burnt influences the amount of charcoal produced (Table 1). Among trees tested, values range from 16.5% for Scots Pine to 25.5% for Mahogany. The variations depend upon 'the hardness and compactness' of the wood (Ure, 1824, p. 315) as well as initial moisture content (Pompe and Vines, 1968). The differences between say wood, grass and moss may, *ceteris paribus*, be expected to be much larger than those given in Table 1 for wood. In forested regions, Erdtman (1972, p. 63) pointed out that 'Devastating forest fires are, however, essentially restricted to softwood forest. Setting hardwood forests on fire is easier said than accomplished', (see also Rowley-Conwy, 1982). This refers, of course, to the Northern Hemisphere coniferous forest experience — the hardwood eucalypt forests of Australia certainly burn!

TABLE 1. Amount of charcoal produced after burning a standard quantity of wood under similar conditions (% of original — moisture content unspecified). Abridged from Ure (1824)

Mahogany	25.5	Sycamore	19.7
Laburnum	24.6	Elm	19.5
Oak	22.7	Ash	18.0
Beech	19.9	Birch	17.5
Holly	19.9	Scots Pine	16.5

The nature of the fire may also be important in controlling charcoal production. The intensity (Komarek *et al.*, 1973), duration, and temperature (Whittaker, 1961; Kenworthy, 1963) are all significant. Schaefer (1974) studied the physical aspects of smoke and found that the more vigorous the fire the finer the ash particles produced. The hydrological conditions of the site (mire and soil) could affect the burning process and thus the production of charcoal.

Peat may itself be a source of charcoal. The practice of mire burning as an aid to stimulate heather growth as a forage for sheep and grouse is commonplace on European moorlands (Kayll, 1967; Gimingham, 1975). Should the peat surface catch fire during such operations, or from arson, or naturally by lightning (Radley, 1965) it may contribute charcoal to the overall depositional sequence. Boyd (1982a, b) offered a mechanism whereby subsurface charcoal may be formed by burning, although Moore (1982) cast doubt upon its efficacy. Subsurface burning of peat is common in the North American midwest.

TAPHONOMIC PROCESSES

Taphonomy describes the processes acting upon an object from the point at which it is produced to the point where it is finally sampled (Webb and McAndrews, 1976; Fagerlind, 1952). The amount of charcoal counted on a slide depends upon the amount originally produced, which is then modified by dispersal and deposition as well as by preservation, sampling, preparation and counting methods.

Dispersal

Wind and water are the primary agents responsible for transporting charcoal from its source to the depositional basins in which it is preserved. Most charcoal reaches a basin by one of the above means, but other mechanisms may be of local importance. A fire burning to the shore of a lake, for example, may kill vegetation that then falls directly into the water. An unusual transport mechanism was postulated by Nilsson (1947) at Holmegaards Mose, Denmark, where the charcoal was associated with a dwelling located on a holm beside the bog. He attributed an extended charcoal layer in the bog to refuse thrown out from the site. When the vegetation growing on or preserved in a basin is a source of charcoal (as in the case of mires), no transport mechanism need be involved.

Wind

Fires of all types produce large quantities of airborne particulates, and according to Hall (1972) may account for a quarter of all primary particulate pollution emitted in the United States. Charcoal emitted into the atmosphere will be dispersed according to the gravitational laws that govern all small particles. Generally speaking, large heavy particles and those with a high ratio of volume to surface area tend to move shorter distances. Green and Lane (1964) note that the terminal velocity of rigid spheres varies from 1.19×10^{-2} cm/sec for particles 2 μm in diameter to 25 cm/sec for those of 100 μm diameter. The aeolian movement of charcoal may also be influenced by the strong convective currents that are often associated with fires. MacArthur (1966), for example, sampled charcoal at a height of 305–457 m above bush fires. The speed and direction of wind and atmospheric washing by rain or snow may also exert an important influence (Clark, 1983a, b). Komarek (1973) noted that charcoal particles and flaming brands of the candle-bark eucalyptus in Australian fires can vary in size from 1 μm to 1.3 m in length, and the larger brands can cause spot fires as much as 24 km ahead of the main fire front.

Water

Much charcoal is also transported hydrologically following fires (Blong and Gillespie, 1978; Cwynar, 1978; Rummery, 1983). Several researchers have found that runoff is increased as a result of burning (Hibbert, 1967). Griffen and Goldberg (1975) determined greater fluxes of charcoal in coastal marine sediments compared with deep-sea sediments and concluded that the higher near-shore values reflected both aeolian and fluvial transport.

Erosion, which often increases as a result of increased runoff following fire, carries both inorganic particulate matter and abundant quantities of charcoal (Swain, 1973; Cwynar, 1978; Patterson, 1978). Post-fire erosion is indicated by layers of charcoal and mineral matter found at the foot of slopes in Arizona (Komarek, 1973) and the British Isles (Durno and McVean, 1959). Tsukada and Deevey (1967) found two to three times more charcoal in sediments near the outlet of a creek feeding Lake Isabal, Guatemala, than 2 km off shore. Patterson (1978) found that in the sediments of Squaw Lake, Minnesota, there was more charcoal near inlet streams than in the deeper, central portion of the lake. Clark (1983a) sampled air- and water-borne charcoal from present-day fires in Australia and concluded that 'more [charcoal] is removed in suspension in water than is carried away in smoke' (Clark, 1983a, p. iv). This conclusion possibly applies to most limnic situations though lakes that receive little surface runoff (e.g. those in kettle and sink-hole depressions) may be exceptions.

Dispersal Time

Much charcoal is probably deposited soon after it is produced. This is especially true for aeolian charcoal, perhaps less so for predominantly fluvially transported charcoal (Blong and Gillespie, 1978). Davis (1967) concluded that both types were rapidly transported to the Maine lakes he studied. Transport time is likely to be shortest in areas of heavy precipitation, where slopes are greatest, where drainage ditches (e.g. for agriculture and forestry) exist, and in lakes receiving heavy runoff from spring snow melt. In drier areas, such as those studied by Clark (1983a) in Australia, prolonged drought could delay the transport of charcoal to a basin. Clark (1983a, p. iii) observed that in such areas 'The sedimentary charcoal record is of fire–rainfall events, not just fires alone', and she has constructed schematic diagrams to show the effects of sampling on fire-history interpretation (Clark, *in press*).

Charcoal production and dispersal may vary seasonally. In Greenland, for example, Fredskild (1973) sampled charcoal rain with pollen traps, and in general he found more charcoal in samples collected in spring and early summer. His findings, however, were not related to the occurrence of regional or local fires or to seasonal variations in wind currents or precipitation.

Under certain conditions regional pollen can be differentiated from local pollen (Janssen, 1966; Fredskild, 1973; Jacobson and Bradshaw, 1981), and the ability to do the same for charcoal would permit identification of regional and local fires. Charcoal dispersal has been little studied, however, and there is as yet no way of knowing to what degree the two types can be differentiated (Bradbury *et al.*, 1975). They might well vary in particle size distribution (Patterson and Nordheim, *in prep.*), but ecological interpretations are complicated by a lack of information on transport rates of different particle sizes and on the degree to which charcoal breakage occurs at any point in the production–reconstruction sequence (Fig. 1). Fredskild (1973) suggested that local and regional charcoal might be separated by comparing results from two basins which, through pollen analysis, can be shown to have produced regional or local pollen records (cf. Jacobson, 1979; Pennington, 1979). An untried but potentially productive means of differentiating the types lies in additional analyses of the sediments in which they occur (see Gorham and Sanger, 1975). Fluvial charcoal may be more abundant in sediments containing large proportions of allochthonous relative to autochthonous material.

Theoretical Models of Dispersal

In the absence of models of charcoal dispersal, Fig. 2 (a–d) is an attempt to utilize ideas developed for modelling dispersal of pollen (e.g. see Tauber, 1965; Jacobson and Bradshaw, 1981) and sand (see Bagnold, 1941). The models presented in Fig. 2 are theoretical and incorporate only wind dispersal. Clearly the total quantity and size distribution of charcoal at a sampling

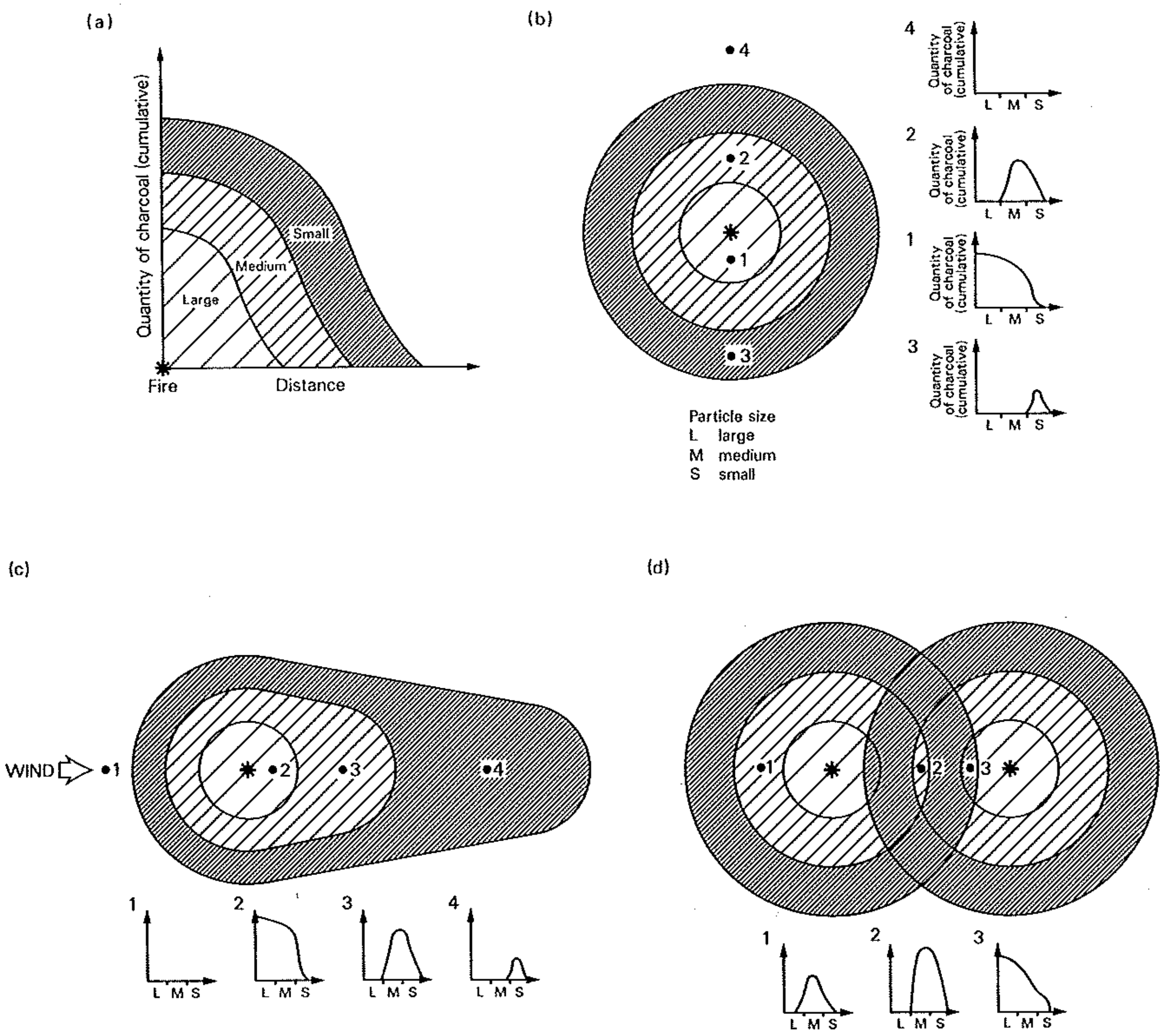

FIG. 2. (a) Theoretical graph showing effect of distance on the quantity and size of charcoal particles deposited after a fire. (b) Two-dimensional map of theoretical charcoal distribution from a fire when wind does not influence dispersal. (c) Effects of wind on the theoretical distribution of charcoal. Scales are the same as for Fig. 2(b). (d) Two-dimensional plot of theoretical distribution of charcoal from two fires occurring simultaneously, in close proximity, and in the absence of wind. Scales are the same as for Fig. 2(b) and 2(c).

site is influenced by variables other than dispersal, and some of these are discussed elsewhere in this paper.

As a first approximation, it is assumed that charcoal dispersal conforms to the distance–decay principle, i.e., with increasing distance from a fire the quantity and size of charcoal particles decreases (Byrne *et al.*, 1977) and that equal quantities of small, medium and large sized charcoal particles are produced. This relationship for a single fire event (cf. Amundson and Wright, 1979) is portrayed graphically in Fig. 2(a).

When viewed in two dimensions [Fig. 2(b)], it can be seen that more charcoal is deposited close to the fire and that the size of particles decreases away from the fire. The possible effect of wind upon the distribution of charcoal is portrayed in Fig. 2(c). Site 1, although relatively close to the fire receives no charcoal. Sites 2 and 3 receive proportionately more charcoal, particularly in the large to medium size ranges, than would be expected under the conditions of model b. Site 4 receives some charcoal in the small size range, whereas under model b it would not receive any. When two fires close to the sampling site burn simultaneously, each fire should contribute charcoal in different quantities and particle size ranges (Fig. 2d).

Although simple, the models presented in Fig. 2(a–d) illustrate some of the difficulties in attempting to reconstruct the intensity, size, distance, and direction of fires from the site of charcoal deposition. In some respects the model may be unnecessarily elaborate. Thus Fig. 2c depicts the wind as a unidirectional entity, whereas it is often highly changeable, even during the brief duration of a single fire (Albini, 1984). The models are also based on the questionable assumption that the convection currents associated with fires will not impart their own special mixing mechanisms on the charcoal rain, thereby negating the spatial size-patterning represented in the models.

Analyses by Backman (1984) of cores from two small (2–3 ha) ponds on the Maine coast suggest that, at least for small catchments, locally produced charcoal has a far greater likelihood of reaching sediments than does charcoal produced regionally. One pond, The Bowl, lies entirely within the boundaries of the great Bar Harbor Fire, which burned 27% of the 2.81 km^2 Mount Desert Island between October 17 and 25, 1947. Sargent Mountain Pond lies a few hundred metres outside the fire's boundary. Pb-210-dated profiles for cores from the two sites showed that the 1947 fire was clearly reflected by a charcoal peak between 3 and 7 cm at The Bowl (Fig. 3a). There was no increase in the abundance of charcoal for sediments of comparable age at Sargent Mountain Pond (Fig. 3b). The results from Sargent Mountain Pond are especially important because they showed no evidence of regional fires which burned more than 86,000 ha of forest in Maine during 1947. The ability of The Bowl pond to register the fire may signify the greater importance of waterborne as opposed to airborne charcoal in the context of these sites (cf. Clark, 1983a).

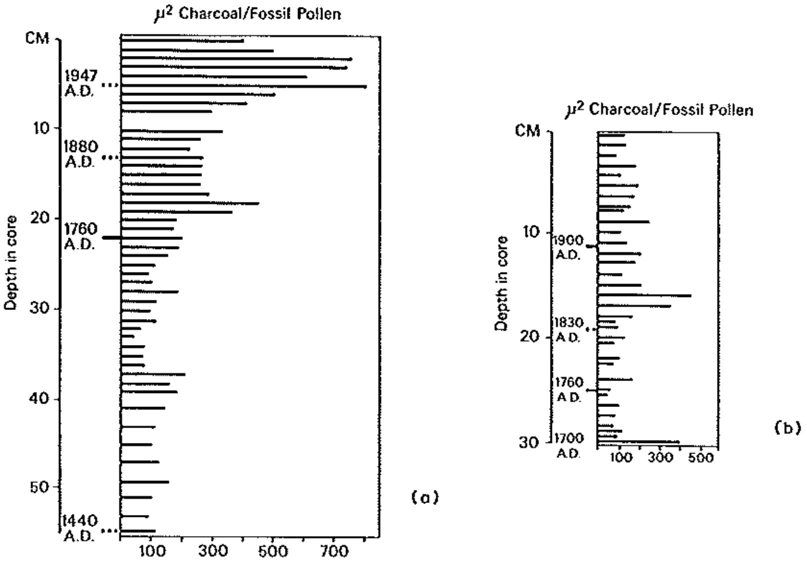

FIG. 3. Profiles of charcoal:pollen ratios for The Bowl (a) and Sargent Mountain Pond (b) on Mount Desert Island, Maine. The entire watershed of The Bowl burned in 1947, whereas the watershed of Sargent Mountain Pond, which lies just outside the 1947 fire boundary, did not burn. Dating of sediments is by ^{210}Pb analysis and extrapolation from a pollen settlement horizon (1760 AD).

Deposition

The precision with which microscopic charcoal reflects the occurrence of fires is a function of transport time from the causal fire, the time that it takes for charcoal to reach the sediment once it enters a depositional basin, its fate within the basin prior to sedimentation, and the constancy of its position in the sediment. Many of these factors must be considered in pollen analysis, and most have been studied. Davis (1967) attempts to answer some of the questions as they apply to charcoal in lakes, while the doctoral thesis of Clark (1983a, see also 1982, 1984, *in press*) represents the most thorough consideration of charcoal analysis to date.

Davis (1967) examined the depositional characteristics of charcoal and determined in laboratory experiments that charcoal fragments become wet and rapidly sink. The applicability of such results to lakes, where surface and sub-surface currents exist is problematical. Renfrew (1973) stated that charcoal has a true specific gravity of 1.4–1.7, but, because of porosity, the apparent specific gravity ranges between 0.3 and 0.6. Her data suggest that charcoal could potentially be quite buoyant.

Charcoal floats to some degree. Thus, while inputs of charcoal might be quantified by sampling aeolian and fluvially transported material, losses from a basin are a function of turnover (replacement) time for the water in the basin. For closed basins no losses will normally occur for biologically inert substances such as charcoal. For lakes and mires drained by one or more outlets, replacement times are theoretically determinable. They usually vary with fluctuating water levels, however, and charcoal losses are exceedingly difficult to estimate. Even if losses can be quantified by direct measurement, extrapolation to the past is rarely possible.

A few studies have tried to detect increased charcoal concentrations by sampling lake sediments shortly after a fire. Fredskild (1973) found increased charcoal in the surface sediments of a small pond in southern Greenland. The core was obtained in July 1970, and Fredskild indicated that the surrounding vegetation appeared to have been burned the preceding year. Bradbury and Waddington (1973) studied the charcoal content of the sediments of Shagawa Lake in northern Minnesota and found abundant charcoal at the sediment surface. They attributed this charcoal to the

Little Sioux burn, a 6,240 ha fire that occurred about 32 km northwest of the lake in May 1971. According to Larsen *et al.* (1975), Shagawa Lake has a hydraulic residence time of only 8 to 9 months, and the fact that a charcoal peak from such a distant fire could be registered in a lake with such a short residence time would suggest rapid deposition. Wright (1974) found no such increase in charcoal in the sediments of lakes within the burn area, however, and Bradbury now doubts 'that the charcoal peak has anything to do with the Little Sioux Fire' (J. Platt Bradbury, *pers. commun.*).

The results from The Bowl (Fig. 3a) indicate that charcoal deposition is rapid, but that redeposition, sediment mixing and/or delayed charcoal transport to the basin can result in charcoal peaks from a single fire that span a decade or more.

Redeposition and Sediment Mixing

Evidence for the rate of deposition of charcoal is not extensive, but even if deposition occurs rapidly enough to avoid losses in open basins other factors may blur the stratigraphic record. Davis (1972) has shown that pollen grains may be redeposited in deeper water after initially settling out near the shore. Rowley and Rowley (1956) note differential downward movement of pollen grains in bogs, although Clymo's (1973) studies indicate that a compact layer of peat often forms by a depth of 5–10 cm. The only reference to peat mixing in charcoal studies known to the authors is that of Iversen (1969) who concluded that mixing was not a problem in the Draved forest cores. He based his conclusion on the ability to detect short, post-fire changes in pollen profiles. Recently completed studies of pollen and charcoal preserved in peat of salt marshes and in freshwater coastal bogs and swamps on Long Island, New York also reveal well-defined patterns of post-fire vegetation changes (Backman and Patterson, *in prep.*). Mixing by burrowing insects and other small animals and trampling by larger mammals (both wild and domestic) is a potential problem in many sites of peat accumulation, however. Frost heaving may also disturb peat accumulating at higher latitudes. The potential for these types of mixing may vary substantially with time as climate, water levels, vegetation, animal populations, and human activity vary.

Post-depositional mixing of sediments could also be a problem at lake sites. Davis (1974) has shown that mixing by tubificids can significantly alter pollen stratigraphy and has suggested that mixing also affects charcoal distributions (Davis, 1967). In the Arctic, shallow lakes and their sediments may freeze completely. Subsequent melting in the spring causes severe disturbance of the sediment (Fredskild, 1973; Jordan, 1975). Mixing and downward movement are a more serious problem for charcoal analysis relative to pollen analysis, because the former usually attempts to identify events occurring on a shorter time scale. If the objectives of a study involve the identification of specific fires, it would possibly be necessary to restrict study to undisturbed sediments, as in the case of annually laminated deposits (Swain, 1973; O'Sullivan, 1983), or to areas where fires occur infrequently. Sedimentation rates would influence how 'infrequent' fires might have to be in order to allow detection, but studies of Maine lakes show convincingly that individual fires at 80- to 150-year intervals are detectable in ponds with sedimentation rates of 0.1–0.2 cm/year (Backman, 1984). The lakes studied do not have laminated sediments. This indicates that bioturbation is not a problem when fire return intervals are long relative to sedimentation rates.

DATA COLLECTION

Unfortunately palaeoecologists have little control over the taphonomic processes that combine to produce fossil assemblages. However, in the collection of data (Fig. 1), they may have a good deal of control over the events that could lead to erroneous results. Consideration of the methods of sampling used to estimate the microfossil charcoal assemblage is therefore of importance although no single method for sampling and quantifying microscopic charcoal has yet been developed and universally accepted.

Site Selection

The selection of sites for palaeoecological reconstruction by pollen analysis has been reviewed by Jacobson and Bradshaw (1981). Some of these ideas may be relevant to the study of microscopic charcoal, notwithstanding the comments made earlier about production, dispersal and deposition. Jacobson and Bradshaw's (1981) work may be used to show that sampling sites of different sizes will receive charcoal from different areas, and Bradshaw and Webb (1985) have recently demonstrated this fact for pollen data. Thus the majority of the charcoal influx of a small site, such as a forest clearing or small pond 25 m in diameter, will be derived from the local area, that is within about 20–30 m of the site. By the same reasoning a large sampling site, such as a blanket bog or large lake, will derive most of its charcoal rain from several hundred metres to several kilometres away. Sites such as small forest clearings and small lakes might provide the most useful records for reconstructing local fires; small bogs and medium-sized lakes could be best suited for reconstructing extra-local fires; and blanket bogs and large lakes should perhaps be used to reconstruct regional fires. Consideration of the size, character and drainage patterns of watersheds surrounding a basin of deposition would seem to be especially important in charcoal studies. Burning often results in deforestation, which can alter runoff and air movement across a site and, as a consequence, may affect charcoal influx (Swain, 1980; Patterson *et al.*, 1983).

Sampling of Deposits

The rate of deposit accumulation could be important in the identification of instantaneous events such as fires (Edwards, 1979; Green, 1983; Clark, *in press*). In situations where sample thickness represents 10–20 years (characteristically about 1 cm), and where contiguous samples are not counted, fires may be completely missed. By contrast, if a sample represents 100–200 years, several fires could be represented or a narrow band of charcoal from a single fire could be averaged with adjacent deposits with little charcoal. The resultant estimate of charcoal content would be low and the single fire would go undetected. In each instance, fire frequency determines whether or not fires will be detected under given conditions of sampling depth and interval, and accumulation rate. In an assessment of problems involved in the choice of charcoal sampling scheme employed, and by the use of model situations, Clark (*in press*) indicates how different schemes can radically alter the apparent fire history even leading to reconstructions of non-existent fire regimes.

Techniques of Analysis

Current methods for sampling and quantifying microscopic charcoal may be broadly classed as those that use the microscope or those that attempt to measure elemental carbon.

Light microscopy

(a) Charcoal determination and identification: One of the major problems in attempting to quantify microscopic charcoal with the light microscope is that of identification (Winkler, 1985). This has been a special problem for one of the authors (DJM) in studies of blanket peat. In samples there are often jet black, opaque, angular particles that are clearly charcoal, and clear or brown amorphous weakly structured particles that are clearly vegetal matter. It is the definition of the intergrade between the two groups where problems may arise. Waddington (1969) solved this problem by counting only uniformly opaque particles. She also suggested that nitric acid treatment would remove pyrite crystals which are opaque, although she circumvented much of the problem by ignoring smaller particles. Davis (1967) prepared reference samples of macerated unburnt and burnt wood in order to assist identification and concluded that 'distinguishing burned wood from other fragments on the pollen slides proved easy in almost all cases' (p. 155). Singh *et al.* (1981) and Swain (1974) were also concerned about this problem and so developed a test procedure to verify their optical identifications. Briefly, Singh *et al.* boiled a set of test samples in concentrated nitric acid for one hour, followed by washing with 5% ammonium hydroxide solution. They suggested that 'the results of the charcoal estimates obtained from these test samples did not vary significantly in their general trends from those treated through the standard procedure' (Singh *et al.*, 1981, p. 25). However, their results show that the samples treated with nitric acid recorded a constant but significantly smaller proportion of charcoal (cf. Clark, 1984). The material removed was attributed to either charcoal broken down by nitric acid or to decomposed plant fragments formed by oxidation.

Some workers have attempted to identify pieces of charcoal to genus or type. Hutchinson and Goulden (1966) tentatively identified charred grass fragments found in the sediments of a lake in central Guatemala and developed theories about the effects of Mayan agriculture on the natural vegetation. Tsukada (1966) identified carbonized fragments of woody species in the sediments of Lake Nojiri, Japan, and related their abundance to land clearing activities by humans. In Minnesota, Waddington (1969) differentiated grass and sedge epidermis from woody tissues and correlated an increase in the relative frequency of the former with a mid-postglacial warm, dry period. Byrne *et al.* (1979) attempted to separate their charcoal into structural types in their analyses of varved deposits in the Santa Barbara Channel, California. They identified, by their various cell patterns, monocotyledon charcoal (assumed to be from grasses) and dicotyledon charcoal (assumed to be nongrass and most likely to represent chaparral species). Such determinations were not always easy (particularly within the dicotyledonous component), and as in an earlier study (Byrne *et al.*, 1977, p. 36) 'only charcoal exhibiting obvious cellular structure was included in the counts'. This last stricture would almost certainly result in a severe under-estimation of charcoal content. Their results (Byrne *et al.*, 1979) reflect an increase in grassland fires during the 1950s and 1960s. Haslam and Maguire (*unpubl.*) investigated the relationship between size and shape of charcoal particles and pollen influx during the Holocene at Broad Amicombe Hole, Dartmoor. Their results, however, indicated that neither size nor shape of charcoal could be used to predict vegetation type.

A problem usually limited to recent sediments (100 years old or less) is that of distinguishing between carbonized plant tissue and smoke microspherules (black opaque spheres composed primarily of iron oxide) produced by the combustion of fossil fuels. Huhn (1974) describes the nature and occurrence of these particles in sediments of lakes near Sudbury, Ontario. Similar particles were found in the sediments of Linsley Pond, Connecticut (Brugam, 1975), Lake Mendota, Wisconsin (Nriagu and Bowser, 1969), salt marsh peats on Long Island, New York (Clark and Patterson, 1984), and several New England lakes (Backman, 1984). Huhn (1974) noted that the greatest number of particles observed were in the smallest portion of the size range, which he gave as 5 to 50 μm (presumably diameter). Their relatively small size, shape, and consistency, plus their restriction to recent sediments, should allow differentiation of these particles from carbonized plant fragments in most but not all cases. Studies of New England lakes (Backman, 1984) indicate that opaque spherules may be produced by wildland fires. In a study of two Scottish lakes, Edwards (1978, p. 194) noted very large amounts of 'minute particulate charcoal which were difficult to estimate quantitatively in recent sediments'. Although this may indicate domestic or heather-burning sources for the charcoal, it is possible that fossil fuel or industrial sources are responsible. More work is needed on the origin and dispersal of these particles.

(b) Breakage: Breakage of charcoal may restrict the ecological interpretation of results obtained from microscopic studies. Combustion processes and fuel type influence particle size as do dispersal and depositional mechanisms and laboratory analysis procedures. In exhaustive tests involving fresh charcoal, Clark (1983a, 1984) found no significant difference in area or number of fragments between control samples and those given complete chemical and physical processing (cf. Swain, 1973), but she thought that the particle size distribution had changed.

Fossil samples are more difficult to assess because other components of the sedimentary matrix, both organic and inorganic, obscure the charcoal and make it difficult to produce true initial control samples, or even satisfactory samples at various stages of, say, a normal pollen preparation procedure. One of us (KJE) has attempted an assessment for a lake-sediment sample from Medicine Lake, South Dakota, although the difficulties involved in the clear discernment of charcoal and of exotic pollen used as a 'spike' make the data tenuous and absolute measurements via the exotic method were impossible. Consequently the data presented in percentage form in Figs 4a and b must be viewed with caution.

The sediment sample from 2,200 cm depth in marl-rich Medicine Lake (Radle, 1981) was gently swirled in hydrochloric acid and the residue which had passed through the 180 μm sieve (which would approximate closely to the maximum sieve size used in pollen preparations), was then run through a further 19 stages of a standard pollen preparation procedure (cf. Faegri and Iversen, 1975) and sub-samples taken at a further four stages for charcoal counting (after boiling in potassium hydroxide; after hydrofluoric acid digestion; after acetolysis; and finally after embedding in silicone oil). Charcoal was measured with the aid of an eye-piece graticule (grid square size of 13.3 × 13.3 μm) and the base units shown in Figs 4a and b are expressed in grid square frequencies as proportions of the total charcoal sum (a minimum of 400 fragments per sub-sample). The original fragments were measured to the nearest 0.25 grid square unit, but for this summary, the raw data are combined to 0.5 unit frequencies. Figures 4a and b show the charcoal data expressed in size classes following arithmetic and geometric progressions respectively (the latter because the number of fragments in each class decreases exponentially as size class increases — see further discussion below). A Kolmogorov–Smirnov test indicated that, although there was no statistical difference between the distributions of data represented by the initial HCl wash counts and the final silicone oil counts, there was a difference between the count after the hydrofluoric acid treatment and either initial or final counts.

The relative nature of the percentage data and the uncertainty associated with the difficult and time-consuming procedure of measuring the size of charcoal fragments make concluding statements problematic. If charcoal counts are to be performed along with pollen in standard preparations, and if there are to be developments in interpretations based on size–class distributions, then the problems that prompted the above exercise need to be investigated more comprehensively. Particular attention should be given to variability among replicate samples, the effects of

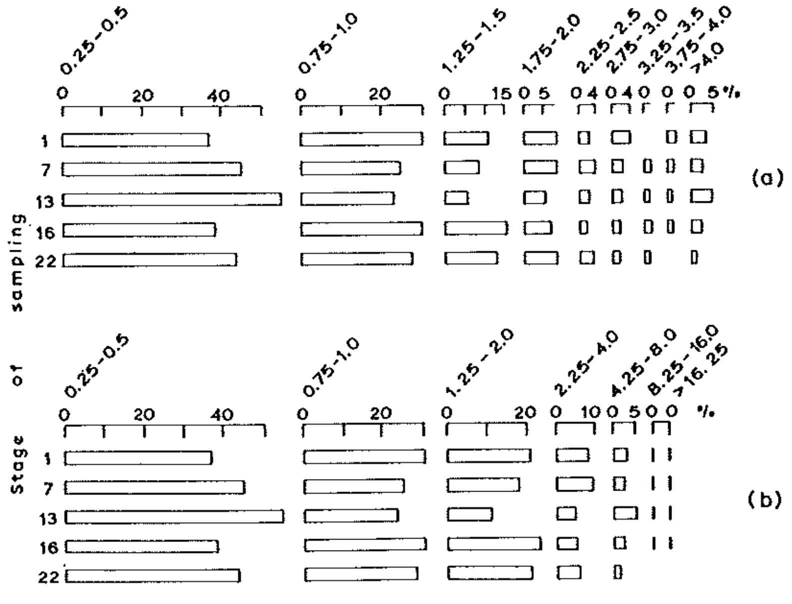

FIG. 4. Charcoal size class data from Medicine Lake, South Dakota. Charcoal at different stages of laboratory preparation: (a) data in arithmetic size classes, (b) data in geometric size classes. Stages of preparation: 1. HCl; 7. KOH; 13. HF; 16. acetolysis; 22. silicone oil.

deposit type and various laboratory procedures. Of interest, for example, is whether the charcoal in a lake deposit has undergone significant breakage by the time it has reached the sampling site and whether airborne charcoal in peat undergoes additional fragmentation during laboratory preparation.

Despite these problems, there often appears to be a characteristic pattern to the distribution of charcoal fragments in arbitrarily assigned size classes. Patterson (*unpubl.*) tallied more than 27,000 charcoal fragments from 44 contiguous samples from Squaw Lake, Minnesota into eleven size classes. More than 90 percent of the fragments were between 85 and 690 μm^2 (the three smallest size classes) (Fig. 5). For individual samples, however, the distribution of fragments in size classes varied. Samples with abundant charcoal consistently had higher proportions of fragments in the larger size classes (Patterson and Nordheim, *in prep.*), and Tolonen (1983) and others have argued that higher proportions of large charcoal fragments indicate periods when fires burned close to a depositional basin.

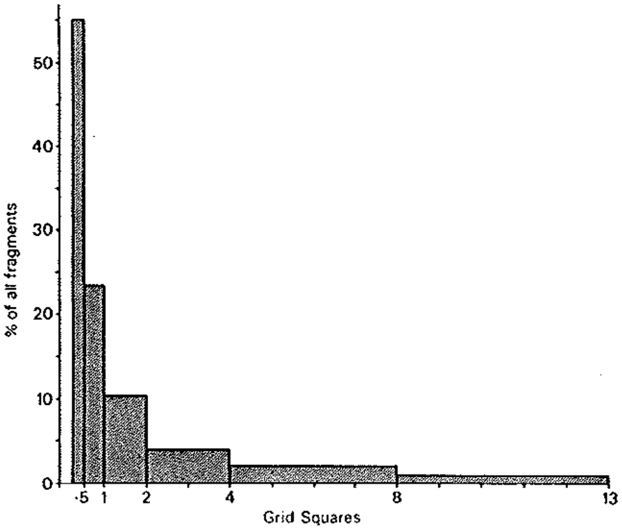

FIG. 5. Proportion of fragments (expressed as %) in six grid square classes for 27,180 charcoal particles measured in 44 contiguous samples from Squaw Lake, Minnesota (Patterson, 1978). Less than one percent of all fragments were larger than 13 grid squares. Fragments smaller than 0.25 grid square were not counted. One grid square is 344 μm^2.

(*c*) *Charcoal measurement*: Methods used to quantify microscopic charcoal under the light microscope have included the counting of numbers of charcoal particles or the measuring of their area by means of point counts (Clark, 1982), classification according to size (e.g. Waddington, 1969) and also shape (Haslam and Maguire, *unpubl.*). Both number and area may be expressed as a percentage of the pollen sum or as a ratio to total pollen (e.g. Swain, 1973; Amundson and Wright, 1979; Maguire, 1983b), as total content per unit of sediment (e.g. Davis, 1967; Mehringer *et al.*, 1977; Innis, 1981), and as influx per unit area per year (e.g. Byrne *et al.*, 1977; Edwards, 1978; Green, 1981).

Numerically, most effort in fire history studies has been invested in optical methods. This probably reflects both the palynological background of most researchers (since they become familiar with the presence of charcoal in their pollen preparations) as well as the versatility of methods that allow easy, albeit sometimes laborious, extraction of data from obviously visible evidence of fire. Examples of such work are summarised below.

(1) Iversen (1934) first observed microscopic charcoal quantitatively in the development of his *landnam* hypothesis. A part of Iversen's first charcoal diagram (Iversen, 1941) from Ordrup Mose, Blaksbjerg, Denmark, is redrawn in Fig. 6. The density of charcoal was estimated by means of cross threads in the ocular and expressed as the number of fragments crossed by a line 10 cm long. On the basis of corresponding rises in charcoal and falls in oak and pine pollen Iversen suggested that fire was responsible for forest clearance. He concluded that the fire was unlikely to be natural because it occurred in deciduous forest. Nilsson (1947), agreed with Iversen that the charcoal represented human activity, but argued that the charcoal was washed from the nearby Mesolithic Blaksbjerg settlement. He disagreed with Iversen's *landnam* hypothesis, but Godwin (1943, 1944) strongly supported it. Iversen (1949) countered Nilsson's criticisms by noting similar vegetation changes at three different sites, arguing that such synchroneity could occur only if the changes were due to the same cause. He argued in the 1949 paper that *landnam* did not occur simultaneously across the landscape. In 1952 Iversen presented pollen and charcoal diagrams from western Greenland in support of his hypothesis and, at the same time, undertook a series of experiments in collaboration with archaeologists to prove that early humans could have affected the vegetation in the manner he hypothesized (Iversen, 1956). Iversen presented more conclusive pollen and charcoal evidence from a study at Draved Forest in southwest Jutland (Iversen, 1964, 1969).

(2) Waddington (1969) presented pollen and charcoal diagrams for Rutz Lake in the Big Woods region of south-central Minnesota. She used a grid square procedure and was the first to introduce the measurement of charcoal particle area in size classes. The area of individual charcoal fragments is determined in terms of grid squares with an eyepiece graticule. Fragments were tallied in grid square classes (e.g. one, two, four squares, etc.) in transects across slides prepared for pollen analysis. The size class tallies in a predetermined number of transects were summed and multiplied by the midpoint of the size class (traditionally the arithmetic mean but the geometric mean would probably be more appropriate — see Fig. 5). This product was multiplied by the area of the grid squares, and the total area for all size classes was determined by summing individual size–class data. Area of charcoal per sample can be expressed in absolute terms by techniques employed in determining absolute pollen frequencies (Birks and Birks, 1980).

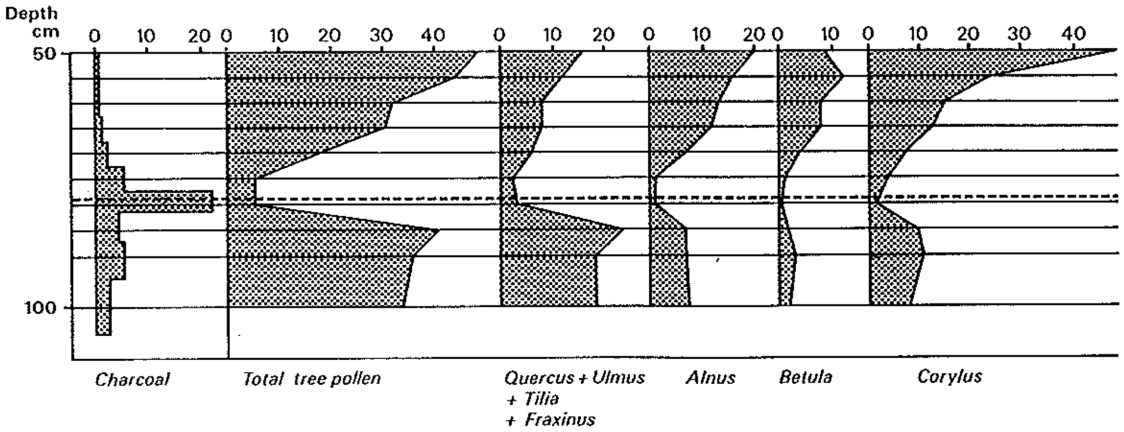

FIG. 6. Pollen and charcoal profiles for Ordrup Mose, Denmark (after Iversen, 1941). Charcoal expressed as number of fragments crossed by a line 10 cm long as determined using cross-threads in the microscope ocular. Pollen expressed as number of grains per cm^2 of the microscope slide. Dashed line shows estimated level of fire.

Area is determined (as opposed to numbers) as it is assumed that large pieces of charcoal contain more 'information' than small pieces. Amundson (1974) theorized that large fragments may be more abundant (relative to small fragments) in sediments deposited shortly after a fire occurs in the area surrounding a depositional basin. The objective of both area and number determinations is the estimation of the quantity of charcoal. In charcoal number determinations all pieces contribute equally to the final sum, and for this reason area determinations are usually thought to give better estimates of charcoal quantity. Area estimates are not completely satisfactory, however, because fragment-to-fragment comparisons assume that all fragments are of the same thickness and density. This is certainly not the case, and for this reason efforts are currently underway to determine charcoal as elemental carbon (see below).

Selected studies using grid square area estimates are summarized in Table 2. Grid sizes depend upon the magnification of the objective and the eye-pieces used by the individual researcher. Choice of grid square size classes has been a matter of individual preference but needs standardization. Guidelines on the number of transects to count per slide do not exist. In specific studies values range from two (Waddington, 1969) to twenty (Swain, 1974).

Waddington (1969) was interested in the entire postglacial vegetation history of the Big Woods. Her samples were spaced too far apart to recognize peaks associated with individual fires, but she did conclude that fires were more frequent and severe during the mid-postglacial warm period and noted an apparent inverse relationship between the occurrence of fire and the degree of tree cover near the prairie–forest border. Waddington counted charcoal and reference pollen on independent transects and, as a result, presented her data as an index. She assumed that the distributions of charcoal and reference pollen were uniform across the slides. Brookes and Thomas (1967) present evidence that suggests, however, that pollen grains may not be distributed uniformly on slides.

TABLE 2. Summary of selected studies employing area estimates

Reference	Site(s)	Grid square size (μm^2)	Grid square classes
Amundson (1974)	Lake of the Clouds Wolf Creek Kirchner Marsh	100	0.5–4.5, 4.5–9.5, 9.5–15.5, 15.5–20.5, >20.5
Bradbury and Waddington (1973)	Shagawa Lake	100	<0.5, 0.5–4, >4
Foster (1976)	Lower LaSalle	316.8	0.25–2, 2–6, >6
Patterson (1978)	Squaw Lake	344.8	0.25–0.5, 0.5–1, 1–2, 2–4, 4–8, 8–13, 13–18, 18–23, 23–28, 28–33, 33–38, >38
Swain (1973, 1978)	Lake of the Clouds	169	0.5–4.5, 4.5–9.5, 9.5–14.5, 14.5–19.5, 19.5–24.5, 24.5–29.5, 29.5–34.5, >34.5
Waddington (1969)	Rutz Lake	255	0.25–0.75, 0.75–1.5, 1.5–2, 2–4, 4–6, 6–8, 8–10, 10–15, 15–20, 20–25, 25–30, >30

(3) The most detailed microscopic studies to date are those of Swain in Minnesota and Mirijami and Kimo Tolonen in southern Finland. Swain (1973, 1974, 1980) sampled the sediments of Lake of the Clouds in northeastern Minnesota at intervals of between two and ten years (Fig. 7). Because of the excellent time control provided by annual laminations (cf. O'Sullivan 1983), he was able to calculate charcoal influxes that he compared to pollen influxes throughout the postglacial period. He identified charcoal peaks that he felt correlated with post-1690 A.D. fires inferred by tree-ring analysis.

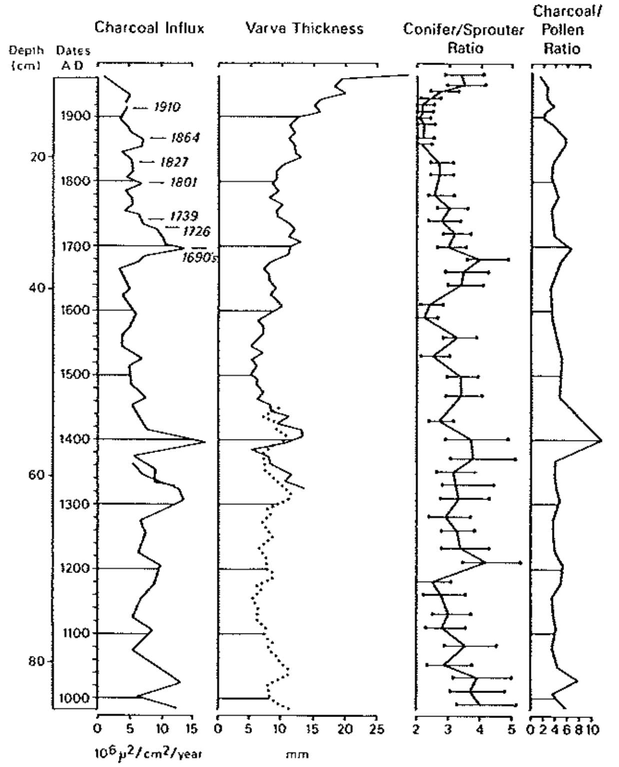

FIG. 7. Selected profiles for Lake of the Clouds, Minnesota showing the relationship between charcoal influx and varve thickness (an index of increased erosion and/or productivity in the lake), the ratio of conifer to sprouter pollen, and the ratio of charcoal to pollen (after Swain, 1973).

Swain devised several indices to aid in identifying charcoal peaks attributable to fire. These included varve thickness (presumed to be greatest after fires as a result of a post-disturbance erosion), the pollen ratio of conifers to 'sprouters' (species that sprout prolifically following fires), and the ratio of charcoal to pollen. Special significance was placed on peaks of the ratio of charcoal to pollen, because Swain presumed that this method of presentation would overcome the problem of false peaks by redeposition of sediment.

Although Swain used area of charcoal in his determinations, he obtained similar results when he expressed his data in terms of numbers of fragments (Swain, *pers. commun.*). He found greater variability in counts from two-year samples than in ten-year samples, as the latter tend to average results. Swain found no significant difference between multiple counts of two samples from the same level. Duplicate sampling by Waddington (1978) also indicated that charcoal counts are reproducible.

Swain has since expanded his studies to lakes in Wisconsin (Swain, 1978) and across much of the northern United States. He showed that the abundance of charcoal in lake sediments is directly correlated with broad regional patterns in fire occurrence (Swain, 1981). His work clearly illustrates the potential use of microscopic charcoal in identifying the effects of fire on vegetation.

(4) M. Tolonen (1978) applied similar techniques to reconstructing the effects of prehistoric humans on landscapes of southern Finland. She calculated charcoal influx to laminated sediments of Lake Ahvenainen and separated charred plant fragments from soot particles. The ratio of the former to the total charcoal was used to estimate the distance of fires from the lake, with high proportions reflecting local fires. Soot is particularly abundant in 20th-century sediments and 'is apparently derived from smoke from human dwellings and industry' (M. Tolonen, 1978, p. 193). K. Tolonen (1983) reviewed several studies employing sedimentary charcoal analyses. He has been particularly concerned with those dealing with peat deposits. He noted that, with few exceptions, 'the accuracy of datings of published charcoal observations in peat is much lower than in varved lake sediments' (Tolonen, 1983, p. 33) and that 'fire history information from peat is generally less useful than that from sediments, because only *in situ* (local) fires leave detectable carbon horizons in peat and very often only where drier margins burn' (Tolonen, 1983, p. 40).

(5) At Lost Trail Pass Bog, Bitteroot Mountains, Montana, Mehringer *et al.* (1977) investigated charcoal in cores collected to examine the environmental history of the area. Examination of the cores by eye and of fresh sediment samples with a dissecting microscope did not reveal the presence of any charcoal. However, 7 of the 81 sediment samples retained on 150 μm screens during pollen analysis, which were examined under a dissecting microscope, contained charcoal pieces of size 0.5–1.0 mm. Examination of slides prepared for pollen counting also showed charcoal to be present in the cores. Microscopic charcoal fragments were recorded, by measurement of longest axis, in eight size classes from 10 to 25 μm and by 25 μm increments to 175 μm and >175 μm. The results show that when charcoal of the smallest class is abundant, charcoal of all size classes is more common. Also, most charcoal larger than 25 μm falls into the 25–50 μm class. Mehringer *et al.* (1977) therefore combined their data to give two size classes (<25 μm and >25 μm). They also state that both size classes are positively correlated at a high level of significance. This they suggest, would result from breakage, and they prefer to interpret the larger fraction as representative of original charcoal in the samples.

According to Mehringer *et al.* (1977, p. 364) 'the variation in charcoal per cubic centimeter appears to reflect depositional environment and deposition rate, and clearly corresponds to pollen abundance'. They cite this as evidence for the fact that the charcoal and pollen were transported and deposited similarly, i.e. 'they were both primarily airborne particles falling into water or upon the bog surface'. They also raise the possibility that large charcoal pieces are indicative of closer fires.

TABLE 3. Comparison of the grid and point count methods for charcoal area estimation for samples from the Bowl (from Backman, 1984)

Depth (cm)	Charcoal/pollen ratios	
	Grid method	Point method
0	400.0	396.6
1	495.4	585.8
2	771.0	1101.2
3	740.5	622.6
4	613.2	878.4
5	801.6	1032.5
6	506.0	458.3
7	416.5	394.0
8	297.0	620.3
10	338.0	307.4
11	266.6	250.5
12	227.0	259.4
13	269.0	521.1
14	267.7	433.9
15	260.8	235.7
16	267.2	131.6
17	291.9	288.6
18	453.5	905.5
19	366.1	371.6
20	177.8	205.2
21	171.1	0
22	195.0	0
23	188.5	291.0
24	148.6	208.4
25	110.2	0
26	92.0	0
27	107.6	0
28	185.3	0
29	116.6	0
30	95.9	0
31	115.8	0
32	69.9	157.2
33	46.8	0
34	81.5	117.4
35	76.3	0
36	75.7	381.4
37	204.3	0
38	156.2	266.5
39	181.7	360.7
41	143.6	193.5
43	116.0	0
45	102.1	0
47	129.6	95.4
49	159.1	0
51	103.2	145.1
53	91.5	163.3
55	114.7	0
$\bar{x}$	246.9	263.6

(6) Green (1981, 1982) working at Everitt Lake, Nova Scotia, used several statistical techniques (sequence-splitting, correlograms, and power spectra) to examine the relationship of pollen, charcoal and erosion of inorganic matter. Pollen concentration and influx were determined with the exotic marker method (Benninghoff, 1962). Charcoal was estimated in three area size classes: 225–900, 900–3600 and >3600 μm^2, with smaller particles ignored. The number of particles counted, weighted for size, was used as an index for charcoal. The inorganic content of samples was determined by combustion (Green, 1981).

Green's studies suggest that the major source of charcoal in Everitt Lake was not from erosion from watershed sediments. This differs from the findings of Swain (1973) and Cwynar (1978) whose results show a correspondence of large pollen influx, charcoal influx and erosion. Green (1982) was also able to show that each fire triggered rapid major forest changes, especially the proliferation of invading tree species that had previously been excluded by competition. Furthermore his results show that fires were more frequent when spruce, pine and birch were abundant and least frequent when beech, hemlock and fir were common. Also, fire appeared to be most frequent in the last 2000 years.

(7) In an investigation of Quaternary vegetation history and fire history in Australia, Singh *et al.* (1981) examined the charcoal and pollen content of sediments at a number of sites. Pollen preparation followed standard techniques and results were expressed on a relative basis. Charcoal particles, expressed as surface area per unit volume of sediment, were estimated by determining the two-dimensional surface area of all visible charcoal particles in volumetrically standardized pollen slides by the use of random points on an eyepiece grid. Clark (1982) describes the method in detail. She offered it as 'a simple and rapid method of estimating the projected area of charcoal' (Clark, 1982, p. 532). Charcoal can be expressed in the same measures as values derived from grid counts (e.g. charcoal to pollen ratios, and charcoal influx). Backman (1984) counted samples from The Bowl using both grid and point-count techniques (Table 3). Comparisons between the two methods give significant Pearson's product moment correlation coefficient *r* values of 0.76, despite the fact that low charcoal content often yields zero values with the point-count method. When these were excluded from Backman's analysis, *r* values rose to 0.86. Analyses of other samples by one of us (WAP) indicate that when charcoal content is low (C:P values less than 100–200) the point count method is as time-consuming as the grid method. A potential disadvantage of the point count method is its failure to categorize charcoal into size classes. Clark (1983a, p. 163) stated that 'size distributions of charcoal particles do not appear to provide useful information', but she acknowledged that 'further research is necessary on this point'.

The long-term data gathered by Singh *et al.* (1981) suggested that increased charcoal was usually linked with establishment and maintenance of the sclerophyll element in the vegetation. They also cited evidence for lack of fires during glacial maxima, attributed to a general lack of fuel. In more recent times there appeared to be evidence

> 'that Aboriginal burning, probably with more frequent and less intense fires than under natural conditions, has been, at least in part, responsible for the ubiquity of *Eucalyptus* and other fire-adapted species over large areas of Australia' (Singh *et al.*, 1981, p. 48).

(8) Innis (1981) and Simmons and Innis (1981) presented a detailed study of prehistoric fire and vegetation on the North York Moors. At Bonfield Gill, Simmons and Innis (1981) examined the lower 100 cm of a 200 cm peat profile containing several layers of wood. In addition to pollen analysis, charcoal was split into macroscopic and microscopic components. The microscopic charcoal or 'soot' (*sensu* Tallis, 1975) was estimated from disaggregated peat mixed with water spread over a gridded Petri dish. At X60, the percentage of each square occupied by charcoal and carbonized material was measured to an estimated replicability of ±3%. From the pollen and charcoal evidence (Fig. 8) they postulated a series of local Forest Clearance Zones (local FCZ). These take the form of either interference or clearance of the forest followed by a period of regeneration. The clearance phases (C) are differentiated from interference phases (I) by their different pollen spectra and the fact that the interference phases are associated with much larger quantities of microscopic charcoal. They suggested that I1, I2, and I3 result from burning of the woodland vegetation by Mesolithic people and that burning took place at or close to the site, because charcoal in the I phases is often quite large (e.g. 15 × 9 mm pieces). In contrast, they suggested that the 'soot' in the regeneration phases (R) probably came from burning in the region but far enough away to provide only background 'noise'.

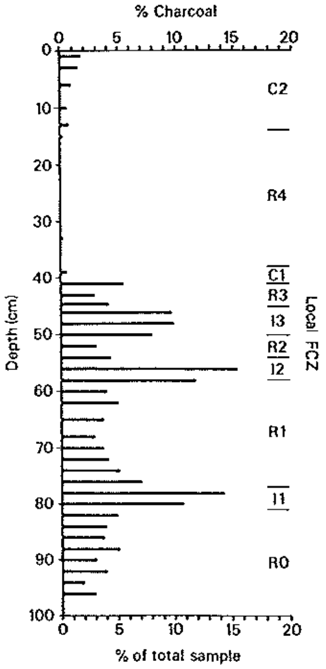

FIG. 8. Pollen and charcoal profiles from Bonfield Gill Head (after Simmons and Innis, 1981). I = interference zone; C = clearance zone; R = regeneration zone.

Inferences concerning the association of fires and natural or anthropogenic causes have been examined by Edwards (1979 and *in press*), Clark (1983b), and Edwards and Ralston (1985). Attention is drawn to the fact that natural fires have occurred throughout prehistory and that domestic fires from within dwellings or settlements will produce charcoal that could coincide with forest clearance phases, leading to the possibly erroneous inference of intentional burning of woodland.

(9) Charcoal analysis of soil profiles has not been a significant part of soil pollen studies (cf. Dimbleby, 1985). Studies at Draved Forest involved mor humus (Iversen, 1964; 1969; but see also Aaby, 1983), which has properties closer to those of peat rather than mineral soil. Whittington (1983) examined the pollen and charcoal content of a soil beneath a Bronze Age bank system in the Black Moss of Achnacree, Argyllshire, Scotland, and did not find a strong characteristic decline in the absolute quantities of pollen (measured as grains per gram of dry soil, cf. Dimbleby, 1962) or charcoal with depth (Fig. 9) although a decline was more pronounced for pollen than for charcoal. Whittington does not discuss the behaviour of the charcoal curve in detail, but it might be hypothesized that the lack of a clear reduction in charcoal is due to the inert nature of charcoal and its persistence at all parts of the soil profile. In contrast, the pollen may have suffered from a general decomposition with age (Havinga, 1974, 1984).

A further example is depicted in Fig. 10a, which shows the results of charcoal and pollen analyses through a profile that includes a mineral soil from the Dam I site of Mesolithic and later age on the Isle of Arran, Scotland (analyses by KJE). Both charcoal and pollen show absolute reductions in concentration with depth. If charcoal is stable within mineral soils, then this may indicate that charcoal production close to the site was less in Mesolithic times than in subsequent periods (this would run counter to notions of the

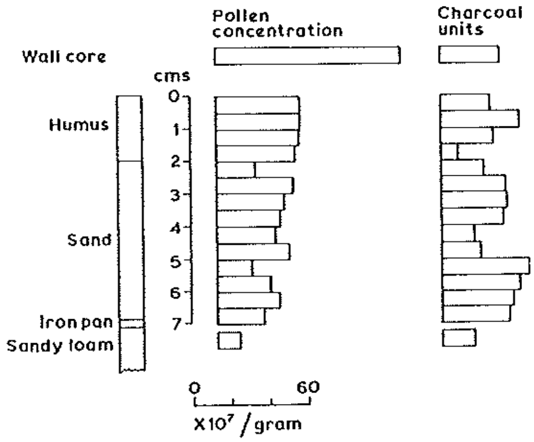

FIG. 9. Total pollen and charcoal concentration data from the Black Moss of Achnacree, Scotland (after Whittington, 1983).

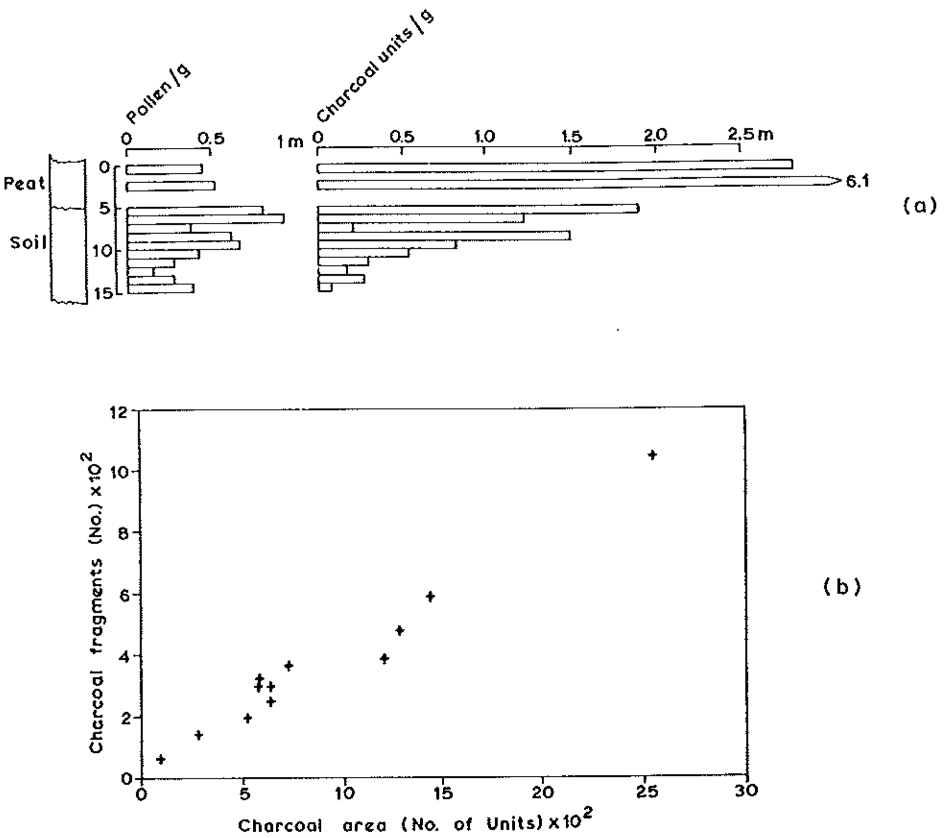

FIG. 10. Data from the Dam I site, Isle of Arran, Scotland. (a) Total pollen and charcoal concentrations. (b) Charcoal areas versus numbers of charcoal fragments.

extensive use of fire by early hunter–gatherers — Simmons *et al.*, 1981). Alternatively, it may be that both charcoal and pollen were moving down through the minerogenic profile before the transportation process was halted by growth of peat. It might also suggest that the destruction of pollen at the site has not been great or that charcoal (or partly carbonized fragments) are being destroyed at depth by some unknown mechanism. The picture may be considerably more complicated, of course, and this is not the place to review the complex issues involved in soil studies. Whittington (*pers. commun.*) has similarly found reductions with depth in absolute amounts of both charcoal and pollen in two palaeopodzol profiles from Benbecula, Scotland.

Figure 10b shows the relationship between total charcoal area and numbers of charcoal fragments for each of the sample levels at the Dam I site. The excellent agreement (Pearson's $r = 0.980$) is in accord with the findings of other workers (Swain, *pers. commun.*; Clark, 1983a). The relationship is not surprising, given the partial interdependence of the data, and it suggests that relative changes in charcoal abundance can be assessed quickly by merely counting charcoal particles along with pollen (cf. Tolonen, 1985), or by using the point count method (Clark, 1982). If charcoal size distributions are considered to be important, however, then there is no alternative but to use some method of measuring fragment sizes.

Image analysis

One of the authors (KJE) has tried image analysis of samples using a Micro Instruments System III analyser which works on the television scanning image principle. Only limited success was achieved owing to the inability of the image analyser to consistently separate charcoal from other black or dark-edged material. Given satisfactory sample pretreatments, suitably pure charcoal samples and appropriate computer programming, then image analysis may result in high-speed accurate charcoal counting.

Electron microscopy

Electron microscopy allows the examination of extremely fine detail in microscopic charcoal whenever the structure survives. Thus it holds the potential for aiding the description of charcoal with respect to its taxonomic origin. Smith *et al.* (1973, p. 270) state that

> 'scanning electron microscope studies on the larger carbon isolates from the (deep-sea) sedimentary column seem promising to compliment and to extend paleopalynological investigations concerned with the extent and types of forests in past geological times'.

Photomicrographs of carbon particles extracted from oil, coal, and wood fly ash are shown in Griffin and Goldberg (1979), although the term charcoal is confusingly applied to all such particles. Komarek *et al.* (1973) issued a preliminary atlas with photomicrographs of various charcoal particles resulting from the burning of vegetation under controlled conditions. They photographed particles originating from three pine, three hardwood, five grass, and four cultivated plant species plus some man-made particulate carbons. The use of electron microscopy in microscopic charcoal studies is still in the developmental stages but holds sufficient potential to merit further study.

Elemental carbon analysis

Although the methods described above are considered to be 'quantitative', they do not measure the actual carbon content of samples. Because the relationship between observed and actual charcoal is unknown and may be variable for different deposits, an argument can be made for attempting to determine elemental carbon directly. The results of efforts to do this have recently become available. The two techniques employed — digestion/combustion and spectrographic analysis — are discussed separately.

(a) Digestion/Combustion: Smith *et al.* (1975), noted that techniques employed to determine carbon in materials of similar composition involve the combustion of carbon followed by determination of the resulting carbon dioxide. They criticized this technique because it included organic and carbonate carbon and lacks sensitivity at or below the 1 mg/l level. G.L. Jacobson, Jr. (*unpubl.*) attempted to overcome the disadvantages of the combustion technique. He prepared test samples by adding known quantities of charcoal to a matrix of fine sand. This synthetic sediment was treated with 30% hydrogen peroxide until oxidation ceased, and the carbon content of the residue was determined by combustion. Treatment with hydrogen peroxide presumably removed all organic carbon, leaving only the elemental carbon as charcoal. The use of a highly sensitive combustion furnace/CO_2 detector allowed satisfactory precision (0.01 mg/l) using small sample sizes. However, recovery of added charcoal was poor (only 3 to 4% in some cases). Apparently the hydrogen peroxide oxidized some of the charcoal in addition to the non-carbonized organic material.

A comparison of three charcoal determination methods has been reported by Robinson (1984 and Fig. 11). Using peat deposits from the Isle of Arran, Scotland, he evaluated charcoal content by: (i) visual estimation of charcoal abundance from pollen sieve washings; (ii) microscopic examination along spaced traverses involving an assessment of total area (cf. Maher, 1972; Swain 1978); and (iii), a chemical digestion method (cf. Tallis, 1975) whereby oven-dried samples were broken up in sodium hydroxide, digested in nitric acid, and combusted at 500°C for 5 hr (this last to determine mineral content). The digestion procedure resulted in a measure of charcoal as a percentage of the initial dry weight of the peat sample. Robinson found that visual estimation provided a general guide to charcoal abundance, but that it takes no account of small charcoal fragments that pass through pollen sieves and that it has all the attendant limitations of subjective methods. The microscope method was considered to be best, especially in the detection of low concentrations of charcoal, although it took no account of larger fragments caught in the preparation sieve. The chemical method failed to detect low concentrations of charcoal and is 'not recommended even as a rough guide to trends in charcoal abundance' and furthermore, it is 'time-consuming, unreliable and of low sensitivity and resolution' (Robinson, 1984, p. 127).

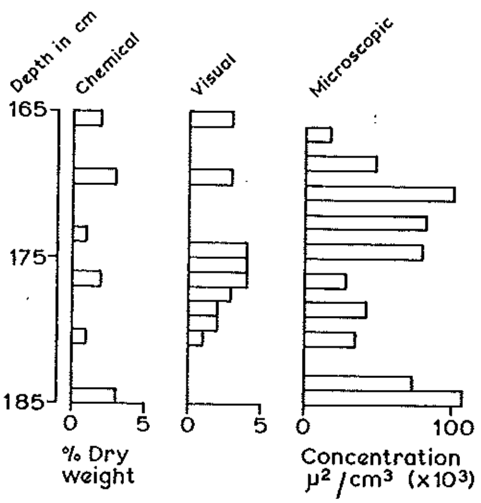

FIG. 11. Chemical, visual (based on sieve-washed material) and microscopical estimation of the charcoal content from the base of peat section TMI, Isle of Arran, Scotland (after Robinson, 1984).

Winkler (1985) has developed a similar chemical assay technique that combines nitric acid digestion with ignition. She determined charcoal as a percent of the dry weight of a 0.5 ml sample by subtracting dry weight after ignition at 450–500°C for three hours from dry weight after nitric acid digestion. The method is 'relatively fast and simple' and 'gives results comparable to counting of microscopic charcoal' (Winkler, 1985, p. 324). She found, however, that comparability between the two methods decreased in post-settlement and lateglacial parts of the cores she examined. Apparently carbon from fossil fuel combustion contaminates recent sediments. Winkler notes that charcoal values (derived from her chemical assay technique) from sediments less than 100 years old cannot be compared to older charcoal values unless wood charcoal and charcoal from fossil fuel burning are separated microscopically. This problem is not trivial, because a principal concern of fire history studies is the documentation of changes in fire regimes associated with the development and expansion of modern societies. Winkler also noted that her assay technique and microscopic techniques do not give comparable results for cores in which sediment type changes. The chemical assay technique underestimated charcoal abundance relative to microscopic techniques when inorganic content of sediments increased in the lateglacial portion of her cores. Fires are often associated with increased erosion (as discussed earlier) and attendant shifts in sediment composition.

(b) Spectrographic analysis: In 1970 Friedel and Hofer observed for the first time the transmission infra-red spectrum of activated carbon. According to the principles elucidated by these researchers, Smith *et al.* (1975) devised a technique for determining the elemental carbon content of marine sediments. Their method requires only 50 mg of dry sediment but is time-consuming (pretreatment can take up to two weeks) and requires special equipment. They tested the reproducibility of their technique on marine sediments and obtained satisfactory results. In contrast to Jacobson's (*unpubl.*) study they found the recovery of carbon in synthetic sediments to be excellent. They used fly ash and petroleum charcoal as carbon sources when preparing synthetic sediment, whereas Jacobson used charcoal in his combustion experiments. It is possible that synthetic sediments prepared with carbonized plant material as a charcoal source would give different results from the synthetic sediments prepared by Smith *et al.* (1975).

Smith *et al.* (1973) first discussed, for ecological studies, the utility of the technique that they developed. They examined the carbon content of deep-sea sediments and found a marked increase in concentrations going from southern equatorial regions northward in both the Atlantic and Pacific Oceans. They concluded that

> 'The most likely source of the carbon in these deposits (we have integrated over about the upper 15 cm of sediment, the past 100 m.y.; the top 0.5 cm, corresponding to the past 5,000 yr, was not included) is the debris produced in forest fires' (Smith *et al.*, 1973, p. 269).

Low values near the equator were attributed to the general non-flammability of tropical forests. The author's conclusions were based on data that are chronologically and geographically imprecise and on very general assumptions concerning the extent and flammability of past vegetation on a hemispheric basis. Their objective, however, was to provide a set of background values of natural (non-anthropogenic) burning processes. Griffin and Goldberg (1975) have attempted to examine in greater detail the fluxes of elemental carbon to marine sediments. They concluded that the higher nearshore values reflected both aeolian and fluvial transportation and that fire-control programmes have had little effect upon elemental carbon influxes.

Microscopy versus Elemental Carbon Analysis

To date, the chief concern of Quaternary researchers has been the detection of past fires, for which some form of quantification of total charcoal content has been necessary. Only the optical methods permit attempts at identifying the source of charcoal. Microscopic methods are the least expensive, if not always the least time-consuming, and they have been applied most widely. One of their chief disadvantages is the lack of methodological uniformity from one study to the next. Breakage may also be a problem for some studies. There have been only limited attempts to analyze the various techniques that have been employed either with respect to their efficiency or accuracy. The use of carbon analysis as a tool in palaeoecological studies is in the early stages of development. The digestion/combustion technique may hold some promise, but it clearly needs further testing. More comparative studies with microscopic techniques are needed as well. A major test of the applicability of carbon analysis rests in its being found to be sufficiently precise chronologically to identify individual fires. A further potential drawback to carbon analysis is its failure to identify charcoal size distributions. It is not known, however, if variations in distributions are ecologically significant and a greater understanding of charcoal production and dispersal is a prerequisite to the future evaluation of microscopic and elemental carbon analyses. Spectrographic analysis has potential, but its use has been limited, and little is known about its potential for application.

It seems too early to abandon standard microscopic techniques in favour of elemental carbon analysis. Some standardization of techniques, as has occurred in pollen analysis, would seem advisable in order to facilitate interstudy comparisons (Tolonen, 1983). Because the proportion of charcoal fragments increases exponentially as size classes are reduced, the selection of a minimum fragment size in optical counts (e.g. the grid and point count methods) strongly influences total area estimates, a problem that may be obviated by the use of elemental methods. Difficulty in separating small charcoal fragments from other opaque objects places a practical limit on the minimum size of fragments that should be counted. A minimum size of perhaps 75–100 μm^2 is reasonable except when sediments contain abundant pyrite. When pyrite is common and removal difficult, an increase in the minimum size of fragments counted to 300–400 μm^2 has been employed (Backman, 1984). This, however, may lead to underestimates of 50–70% of total charcoal area due to the exclusion of smaller charcoal fragments. When grid-counting techniques are employed, size classes should follow a geometric progression (e.g. ¼–½, ½–1, 1–2, 2–4, 4–8, 8–16 grid squares), again because the number of fragments in a given size class decreases exponentially as size class increases.

Magnetic Measurements, Charcoal, and Fire History

Burning of soils can lead to the formation of magnetically enhanced secondary ferrimagnetic oxides (Le Borgne, 1955; Rummery *et al.*, 1979). Erosion of soils following a fire and their deposition in a lake creates a long-term sedimentary record. Down-profile changes in such rapidly measurable parameters as magnetic susceptibility (χ) and saturated isothermal remanent magnetisation (S.I.R.M.) can then be used as an aid in fire history, because sediments derived from burnt soils can produce magnetic values several orders of magnitude greater than those of unburnt soils (Rummery, 1983). These may be used independently of charcoal measurements, but if it can be shown that the magnetic data bear a direct relationship to those from charcoal then χ and S.I.R.M. may provide a suitable surrogate for charcoal determinations — all the more so because magnetic measures are rapid and non-destructive of materials (Thompson *et al.*, 1975; Oldfield, 1977). Such links are not, however, unequivocally direct. The chemical condition beneath burning vegetation may be insufficient for the formation of magnetic oxides, especially if soil temperatures are too low or a reducing environment is not present. This might be important in a controlled burn situation (cf. slash-and-burn agriculture) where temperatures may be lower than hotter wild fires and in areas where wild fires burn in the spring when high soil moisture conditions limit soil heating. If erosion does not follow burning, then the magnetic evidence for a particular fire may be lost, aggregated with the record of later fires, or merged with sediment whose magnetism derives largely from authigenic formation at the mud–water interface. The catchment areas of the inwashed magnetically enhanced soils and the charcoal may differ markedly, necessitating a careful evaluation of the respective fossil records (Edwards, 1982). Comparative magnetic and charcoal data have been reported from Scotland (Edwards, 1978, 1979), France and Finland (Rummery 1981, 1983) (Fig. 12a and b). There is room for much more research in this area, but for the moment it has been suggested 'that the technique should be used to complement rather than replace other more time-consuming techniques for identifying fire records' (Rummery, 1983, p. 57).

CONCLUDING POINTS

In contrast to pollen analysis, microscopic charcoal studies have been neglected. At all stages between the fire and its reconstruction (Fig. 1) there are processes requiring study by palaeoecologists, sedimentologists, climatologists and other workers. Items that arise from discussions in this paper include:

(a) The spatial relationships between fire size, vegetation types and the impacts of fire on charcoal and pollen production. For example, does a small fire of area 1A and in vegetation composed of P and Q have the same impact on the fossil record as a larger fire of area 10A in vegetation composed of Y and Z? The distance of fire from a sampling site may be important also.

(b) Charcoal dispersal and the choice of sample site. We are not aware of any theoretical or empirical models relating to the removal of charcoal from a burned area to a site of deposition. An understanding of transfer processes may be an important factor in deciding the usefulness of a particular type of site for specific investigations. If airborne movement of charcoal is as important as water-borne movement, then a mire site could provide as good an indication of fires on adjacent areas as a lake site (Clark, 1983 and Tolonen, 1983 suggest the opposite). Can mire sites which receive charcoal chiefly from aeolian sources provide a more reliable picture of regional fire history than lake sites which receive charcoal from both aeolian and fluvial sources? Are soils more useful for providing an indication of local fires, or does the soil–charcoal relationship suffer from the shortcomings evident in the soil–pollen relationship (Dimbleby, 1985)?

(c) The site of deposition. Do peat or lake deposits act in different ways as reservoirs of charcoal? Is there a general blurring of the lake-based record as a result of sediment movements? Does the burning of a peat bog surface and the production of *in situ* charcoal totally destroy the contemporary microscopic charcoal record as well as that from lower older layers?

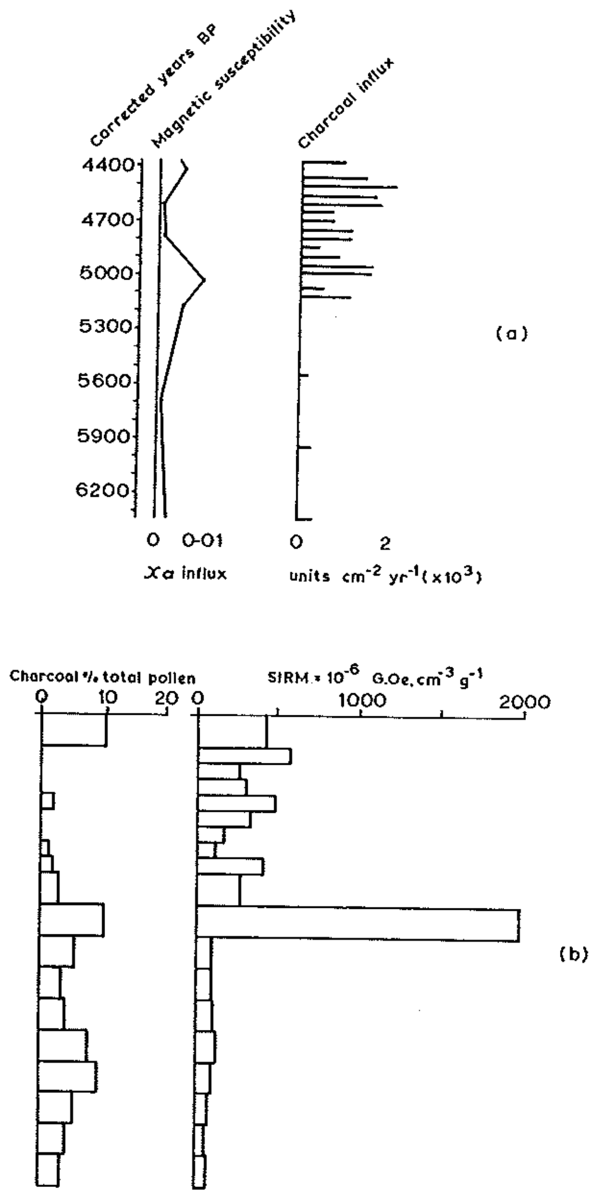

FIG. 12. Charcoal and magnetic data. (a) Charcoal and magnetic susceptibility 'influx' data from Braeroddach Loch, Scotland (after Edwards, 1979). (b) Charcoal and S.I.R.M. data from core PB6, Lake Biscarrosse, France (after Rummery, 1983).

(d) Sample preparation and measurement. How far do laboratory procedures (especially pollen-based ones) alter the charcoal record (cf. Clark, 1984)? Does breakage of microscopic charcoal diminish or even render useless the size distribution of charcoal microfragments, or is a size signal still retained in the samples? Is that signal of any ecological significance? Has the comminution of lake-sediment charcoal already reached an advanced stage as a result of its travel to the lake site? Does charcoal in a peat deposit experience its maximum breakage at the laboratory preparation stage? Is charcoal in a mineral soil subject to constant abrasion or damage due to down-profile movement in a coarse fabric environment? If the area–number relationship of charcoal microfragments is significantly correlated, then is there much to be gained in measuring total charcoal areas or even point sample estimation? (The latter is most likely to be preferred in situations where the concentration of charcoal particles is extremely high.) Can image analysis be developed to at least measure opaque microfragments that are known to be predominantly charcoal? Can other chemical procedures supersede optical counting? How far can magnetic measurements provide a satisfactory surrogate for the determination of fire events?

(e) Identification. Apart from the identification of charcoal as opposed to non-carbonized material (e.g. pyrite or fragmented *Cenococcum geophilum* sclerotia) can advances be made in identifying microscopic charcoal beyond, at best, monocotyledonous or dicotyledonous fragments? Is the scanning electron microscope the only tool that can improve identifications (cf. Komarek *et al.*, 1973)?

(f) Temporal relationships and resolution of fire events. What is the time separation between the production of charcoal and its deposition? Are usual pollen sampling intervals too great to provide anything other than a general indication of fire? Is contiguous, perhaps high-resolution sampling a necessity in order to pick up essentially discrete fire events (cf. Garbett, 1981)? Can radiometric age determinations provide a satisfactory temporal framework for fire history, or should annually-laminated sediments be the preferred sample medium?

The role of natural and human-induced fire in ecosystem change is not in doubt. The fullest understanding of past environments cannot ignore fire, and charcoal analysis of deposits would seem to offer perhaps the most comprehensive means of reconstructing fire events. The fact that the microscopic charcoal record can be validated against other measures common in Quaternary research is a great advantage and should encourage workers to consider the adoption of at least some of the rapid methods of charcoal counting. Developments in the study of microscopic charcoal will depend upon the efforts of many people and their judgment as to the utility of charcoal analysis for their own research programmes.

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